Identifying Galaxy Mergers Through Spatially-offset Radio AGN

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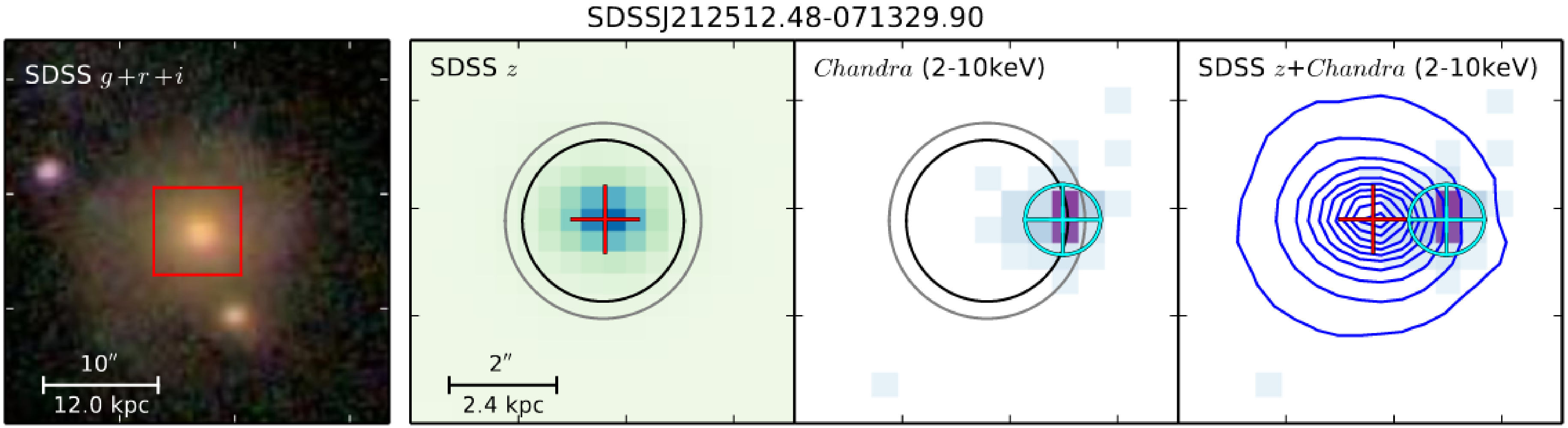
Introduction

Recent or on-going galaxy mergers can be identified through a disrupted galaxy morphology, or, additionally, a spatial or kinematic offset between the active galactic nucleus (AGN) and the host galaxy. Following a galaxy merger, the two SMBHs should form a dual SMBH system.

We are prompted by a recent claim by Barrows et al, 2016, that X-ray AGN are often found offset from the centres of their host galaxies.

Here we look for spatially-offset radio AGN by comparing the positions of compact sources in the Cosmic-Lens All Sky Survey (CLASS) catalog with those of the SDSS galaxy catalog.

Offset AGN from Chandra (Barrows et al, 2016)

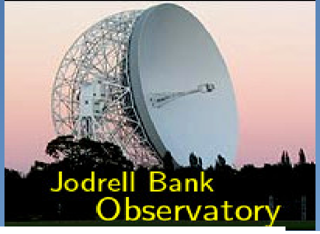


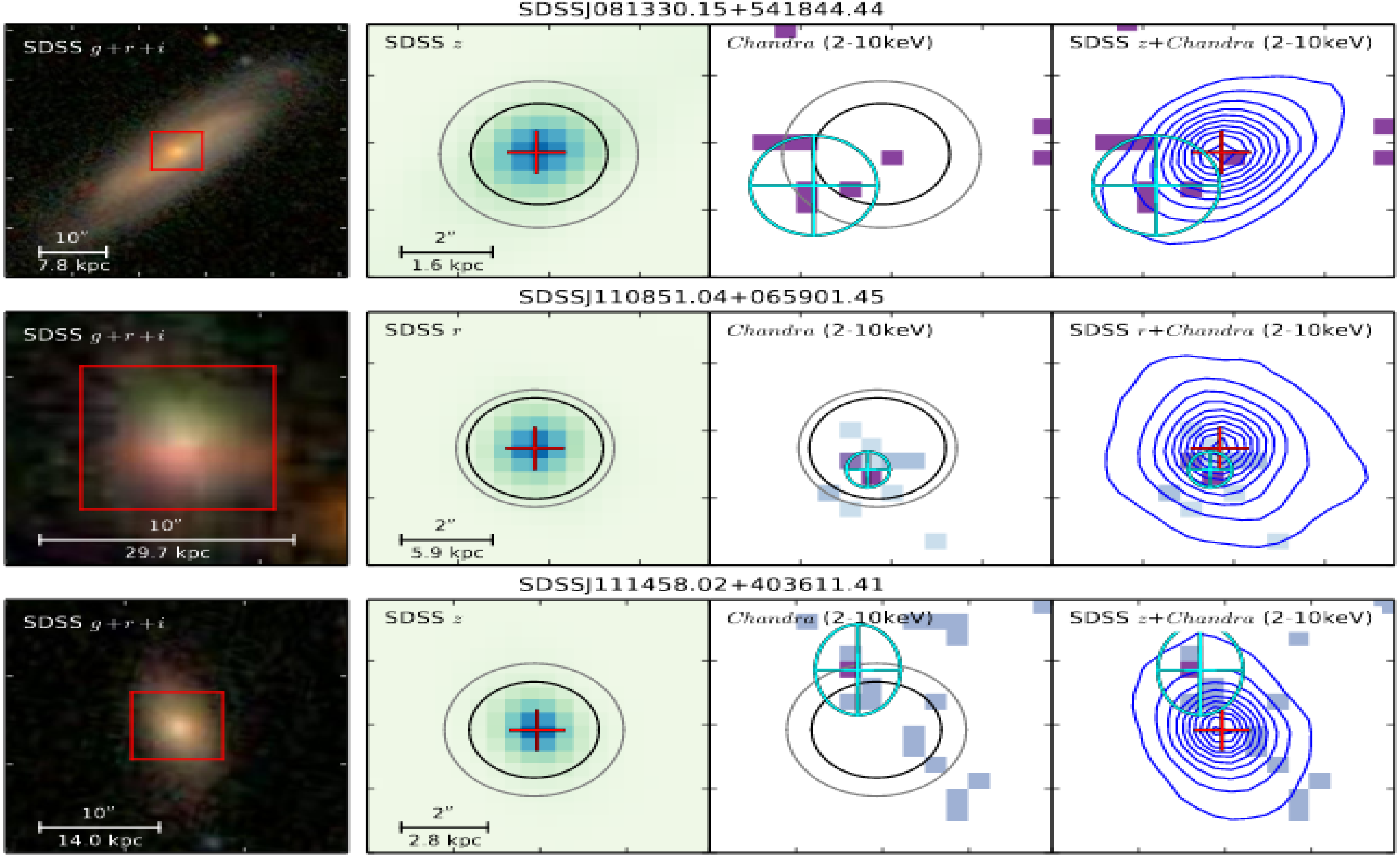
Search for spatially-offset AGN using archival Chandra ACIS images

Sample of **48** Type II AGN from the SDSS galaxy catalogue – **18** were found to have X-ray AGN spatially offset from the galactic stellar core by between 0.6 and 17.4 arcsec. This is **37.5 %**.

Only galaxies found in the OSSY catalogue of emission and absorption lines measurements were included.

Offset AGN from Chandra (Barrows et al, 2016)





Barrows et al 2016

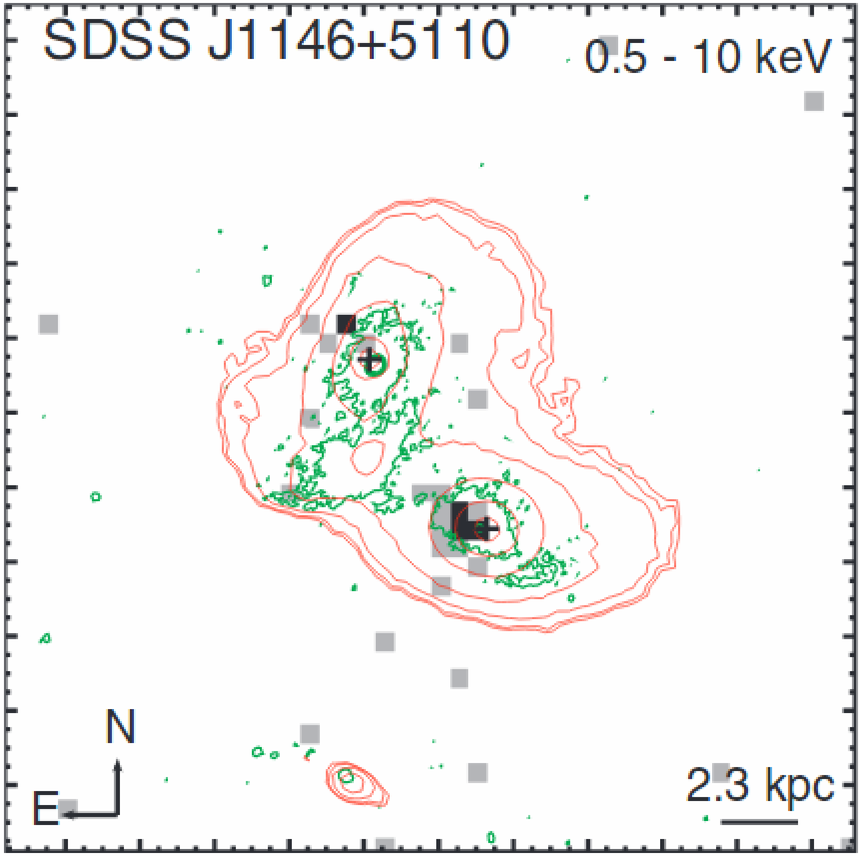
Offset AGN: What to look for

1) Merging Black Hole Binaries:

Supermassive black hole binaries in post-merger galaxies, in the process of coalescing.

Usually expect a see a double peak in the brightness profile, but it is possible that only one source is detectable.

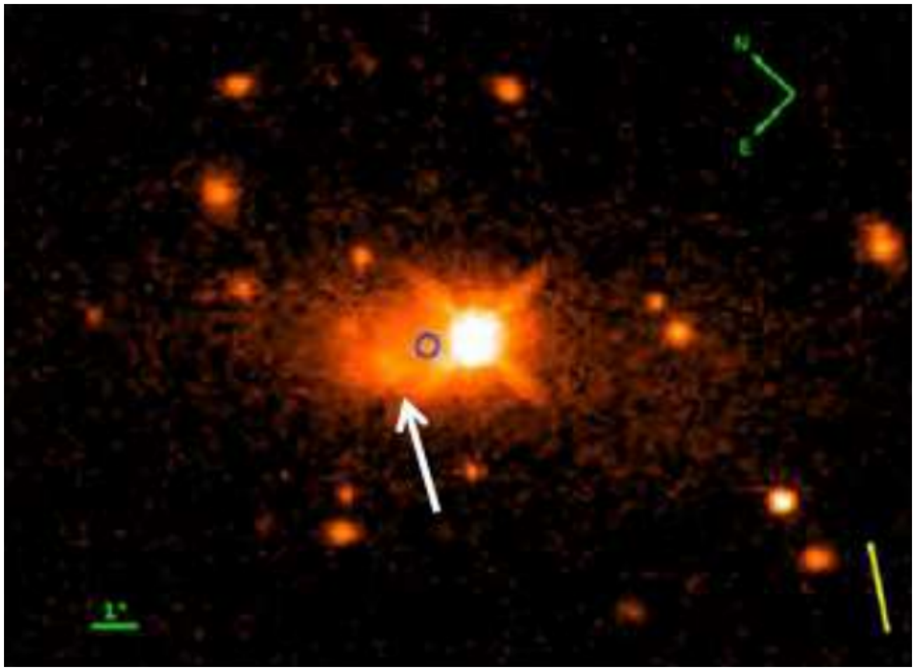
During the 'pairing' phase, the two black holes are still resolvable at cosmological distances (with a separation of a few tens parsecs to a few tens kiloparsecs).



SDSS J1146+5110
Liu et al, 2013

Offset AGN: What to look for

2) Recoiling Black Holes:



QSO 3C 186
Chiaberge et al, 2016

Caused by the anisotropic emission of gravitational waves (Peres 1962; Beckenstein et al 1973).

Typically, for non-spinning black holes, the expected velocity is around a few hundreds of km s^{-1}, or less.

Broad- and narrow-line regions expected to show different velocity shifts, as the BLR is dragged out with the recoiling BH.

Fundamental plane of black hole activity

An empirical relationship between radio luminosity, X-ray luminosity and black hole mass.

Fundamental plane holds across many orders of magnitude in mass, from X-ray binaries to AGN.

$$\log L_r = \left(0.60^{+0.11}_{-0.11}\right) \log L_x + \left(0.78^{+0.11}_{-0.09}\right) \log M_{BH} + 7.33^{+4.05}_{-4.07}$$

Merloni et al 2003

Emission from the supermassive black hole is easier to identify in a crowded field by using radio rather than X-ray, because of the 'boost' from the black hole mass term.

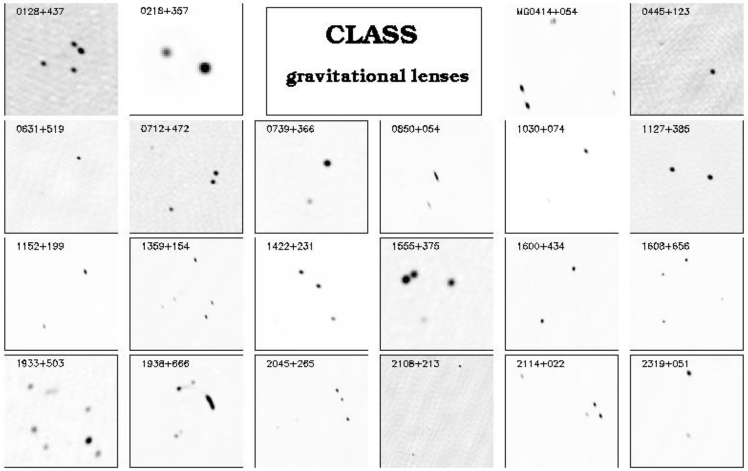
CLASS: Cosmic Lens All-Sky Survey

Myers et al 2003; Browne at al 2003

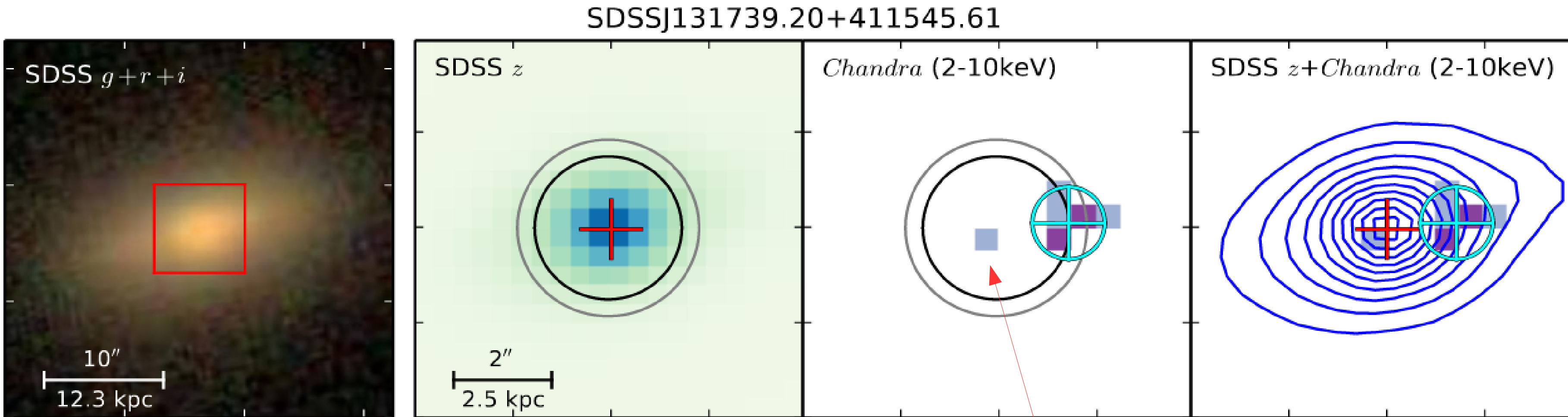
A search for gravitationally lensed compact radio sources. CLASS has identified 22 gravitational lens systems.

Declinations above approx 0 deg, observed first with the VLA, and then follow-up observations with MERLIN and VLBA.

16,682 pointings, 23,418 components detected.



http://www.jb.man.ac.uk/research/gravlens/class/class.html



Barrows et al 2016

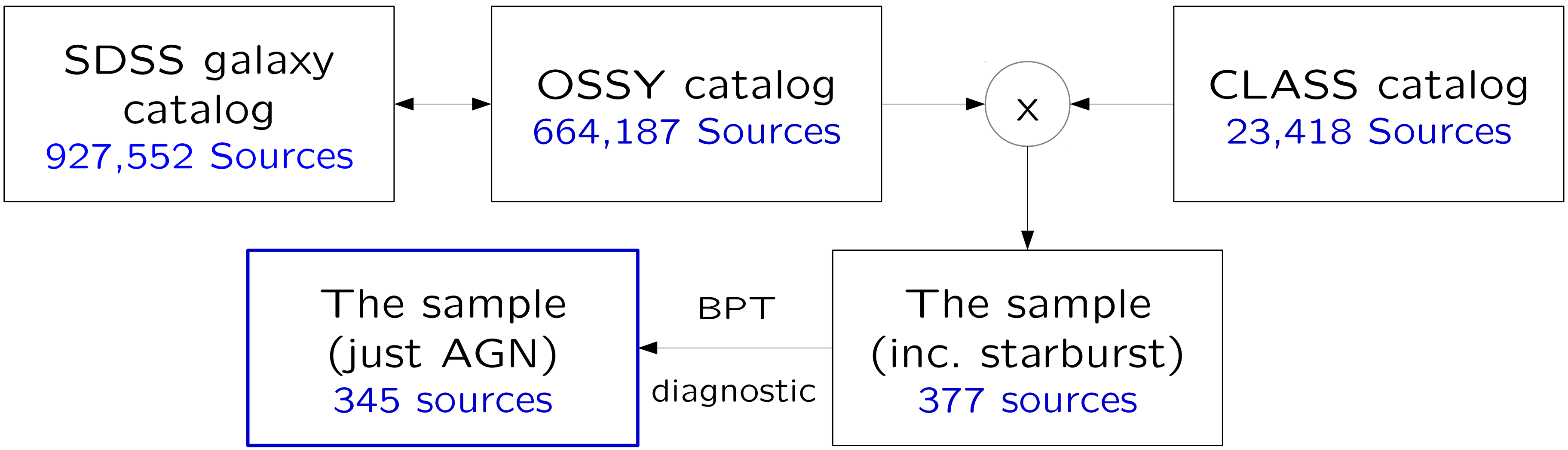
CLASS: 171.4 mJy
compact source

Barrows et al (2016) identified 18 offset AGN from a sample of 48 AGN using Chandra images.

In one of these 18 AGN the only detected compact radio source is coincident with the galaxy centre, and NOT the brightest X-ray source.

The sample

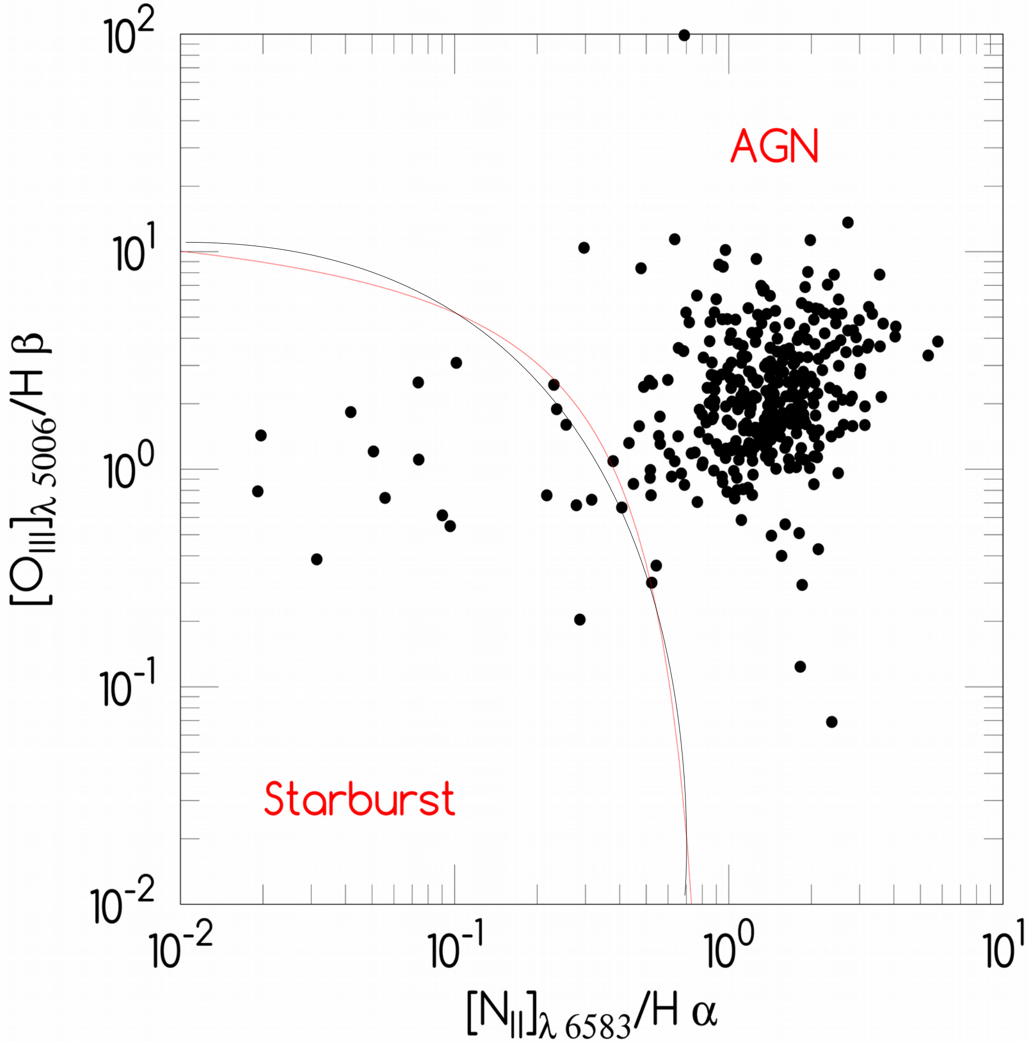
Sample constuction:



OSSY catalog (Oh et al, 2011) crossed matched to the CLASS database to find sources that lie within 10 arcsec.

Matches checked by examining SDSS images, resulting in 377 confirmed matches.

Starburst galaxies are elimated by using a BPT diagram, and the AGN/starburst demarcation curve of Kauffmann et al (2003). The final sample contains **345** AGN.



Exclude starburst galaxies using BPT diagram

Use the demarcation curve of Kauffmann et al (2003):

Galaxies classified as starburst if

$\log([O_{III}]/H\beta) < [0.61 / (\log([N_{II}]/H\alpha) - 0.05)] + 1.3$

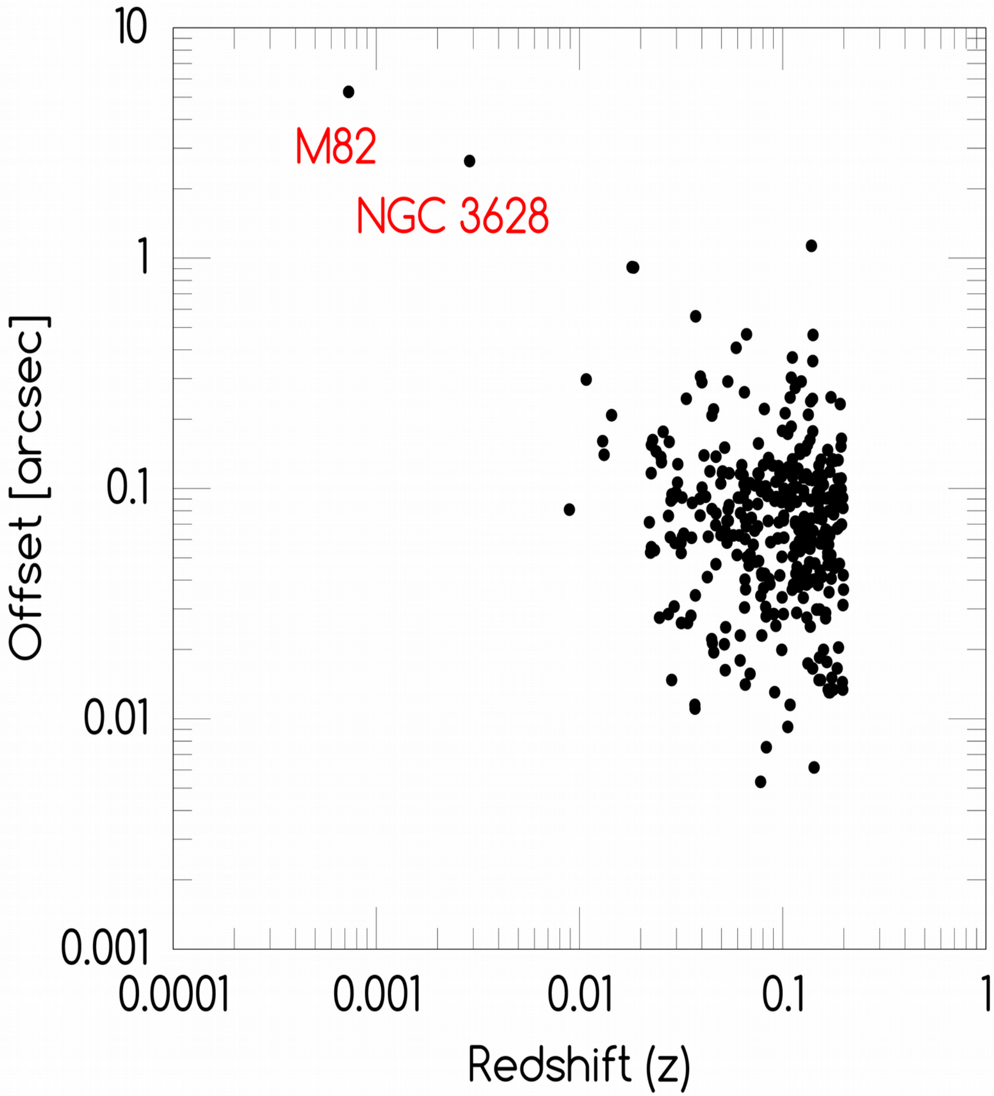
and

$\log([N_{II}] / H\alpha) < 0.05$

Only 22 galaxies rejected, leaving a sample of 345.

Skipper & Browne, submitted to MNRAS

CLASS (Radio) and SDSS position cross-matching



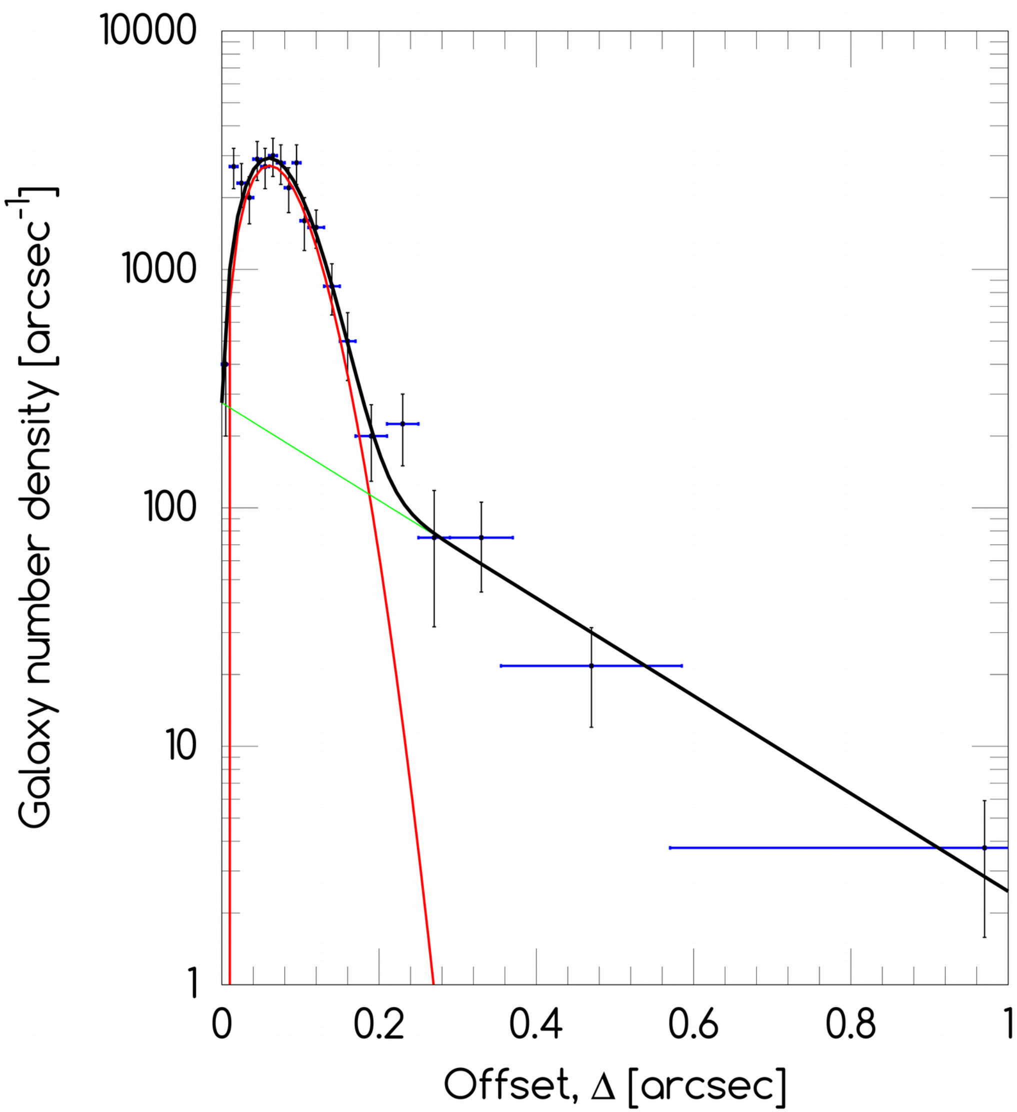
Check for correlation between redshift and offset.

Once M82 and NGC 3628 are removed then there is only a weak anti-correlation between redshift and radio/optical offset (Pearson correlation coefficient, $r = -0.127$).

If the correlation had been strong, then there would be a risk that the offset was caused by greater positional uncertainty in nearby galaxies, as is the case in M82 and NGC 3628.

Skipper & Browne, submitted to MNRAS

CLASS (Radio) and SDSS position cross-matching



Histogram of CLASS/SDSS offsets

Fitted with a Rayleigh distribution, with σ = 60.5 milliarcsec (red line).

This component describes the uncertainty in the SDSS and CLASS positions.

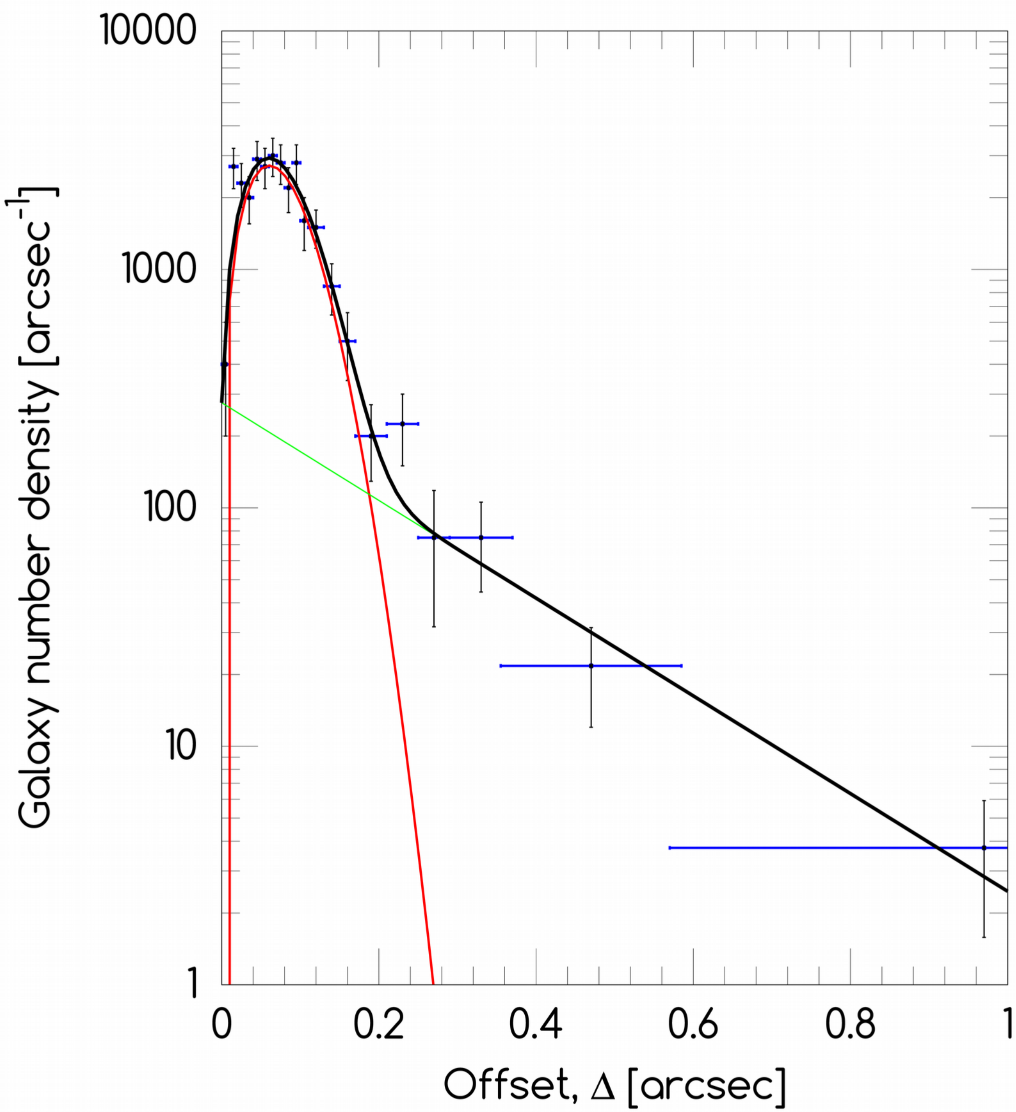
Second component forms an exponential tail of the form exp(-4.72Δ).

This component describes sources which include genuinely offset AGN.

The fit quality is good: χ^2_{red} = 0.81, for 20 degrees of freedom.

Skipper & Browne, submitted to MNRAS

CLASS (Radio) and SDSS position cross-matching



Rayleigh distribution:

$P_R(\Delta) \propto (\Delta / \sigma^2) \exp(-\Delta^2 / 2\sigma^2)$,
$\sigma = 60.5$ mas

Exponential tail:

$P_E(\Delta) \propto \exp(-\lambda\Delta)$, $\lambda = 4.72$

Integrate $P_E(\Delta)$: **59** sources (**17%** of the sample of 345).

Many of these sources are not genuine offsets – i.e. background AGN, confusion from dust lanes, etc.

Comerford & Greene (2014) estimate that between **4** and **8%** of AGN are offset, based upon velocity offsets in optical spectra.

The different results from X-ray and radio-selected samples

By matching the CLASS sources to OSSY we follow the same method used by Barrows et al (2016), who matched the positions of X-ray sources detected with Chandra to the OSSY catalog.

	X-ray Selected (Barrows et al 2016)		Radio Selected (This work)	
Sample Size	48		345	
0.6" $<$ Offset $<$ 17.4"	18	(37.5%)	3	(0.87%)
0.15" $<$ Offset $<$ 17.4"			41	(12 %)

Barrows et al applied a couple of X-ray requirements to their sample selection:

- Hard X-ray source detected within SDSS Fiber
- X-ray source passes L_X ($L_{2\text{-}10\ \text{keV}} > 10^{42}$ erg s^{-1}) or HR criteria ($(H - S) / (H + S) \geq -0.1$)

Results – Summary

15 galaxies with CLASS/SDSS offsets of between **150** and **200 mas**
26 galaxies with offsets of between **200** and **600 mas**
3 further galaxies with an offsets of more than **600 mas**

Total: **44** galaxies with offsets $>$ **150 mas**.

38 of these galaxies have flux densities $>$ **8 mJy**

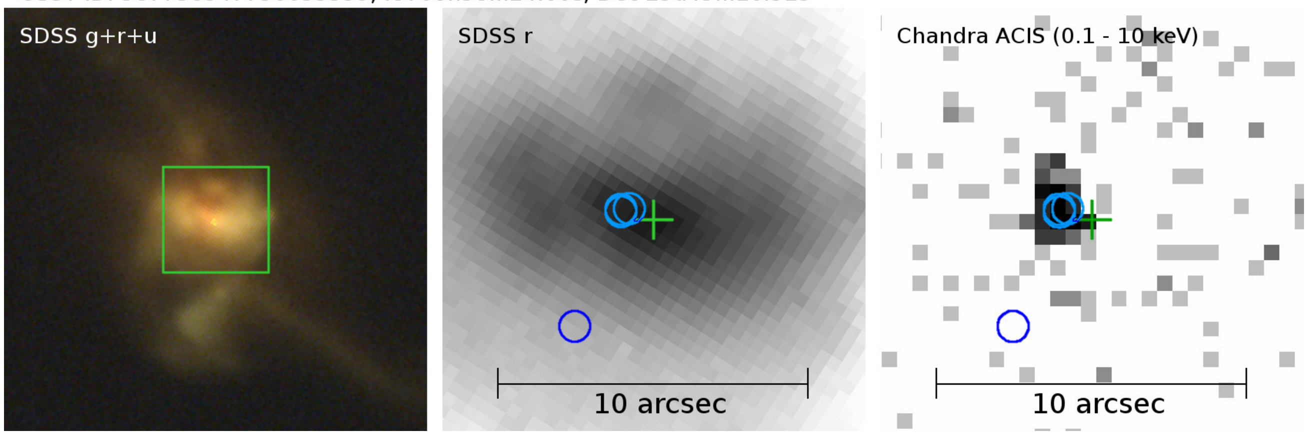
- At least **5** are clearly interacting galaxies (including Mrk 273 and Arp 220).
- **4** have dust lanes
- Several are disk galaxies
- **1** turns out to be a radio lobe lensed by an intervening galaxy

70% of galaxies with offsets above **150 mas** cannot be described by the fitted Rayleigh function. Good domain in which to look for offset AGN.

Results – Known interacting galaxies

15 galaxies with CLASS/SDSS offsets of between **150** and **200 mas**
26 galaxies with offsets of between **200** and **600 mas**
3 further galaxies with an offsets of more than **600 mas**

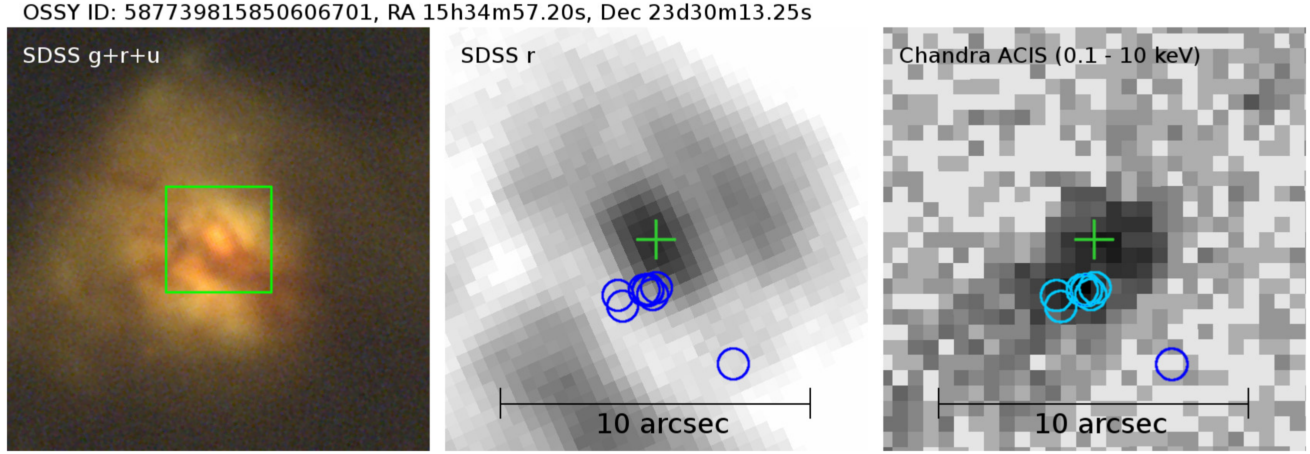
OSSY ID: 587738947736633359, RA 08h38m24.00s, Dec 25d45m16.31s



SDSS J083824.01+254516.4 **(Arp 243)**: A well-known merging galaxy ($z = 0.0185$) with a CLASS/SDSS offset of 911 mas (346 pc). Both Chandra and CLASS sources are offset from optical nucleus.

Skipper & Browne, submitted to MNRAS

OSSY ID: 587739815850606701, RA 15h34m57.20s, Dec 23d30m13.25s

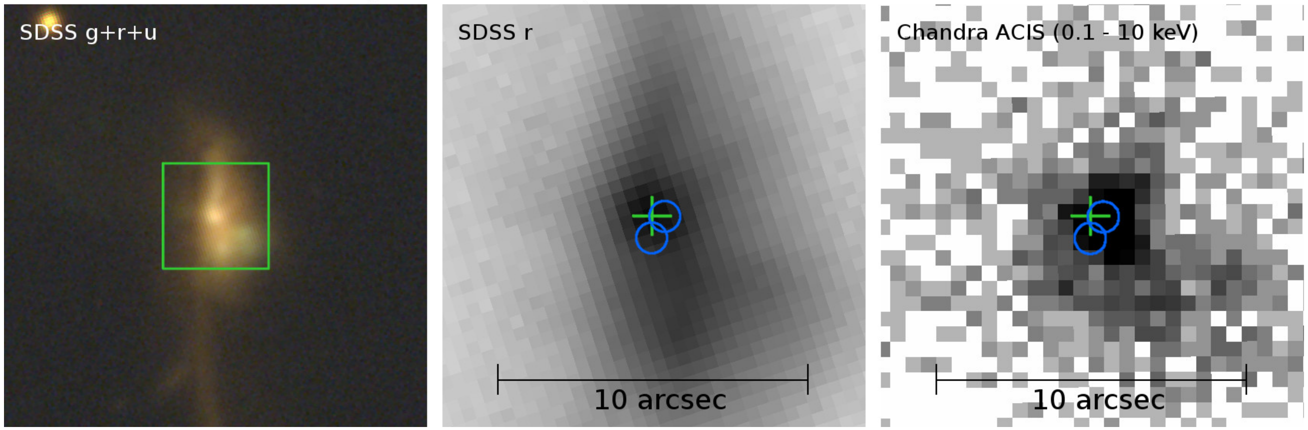


SDSS J153457.21+233013.3 **(Arp 220)**: A well-known merging galaxy ($z = 0.0181$) with an observed offset of 914 mas (341 pc). Multiple compact radio sources.

Results – Known interacting galaxies

15 galaxies with CLASS/SDSS offsets of between **150** and **200 mas**
26 galaxies with offsets of between **200** and **600 mas**
3 further galaxies with an offsets of more than **600 mas**

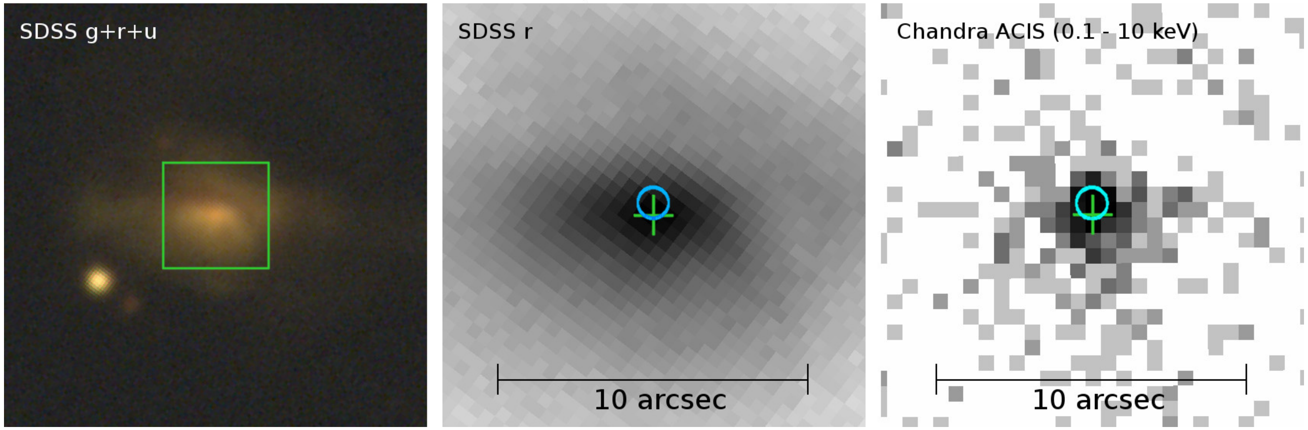
OSSY ID: 587735666377949228, RA 13h44m42.16s, Dec 55d53m13.53s



SDSS J134442.13+555313.5 **(Mrk 273)**: A well-known merging Seyfert 2 galaxy (z = 0.0373) with a CLASS/SDSS offset of 559 mas (425 pc). U et al (2013) confirmed that this galaxy hosts a dual AGN system.

Skipper & Browne, submitted to MNRAS

OSSY ID: 587725551741370430, RA 09h35m51.60s, Dec 61d21m11.34s

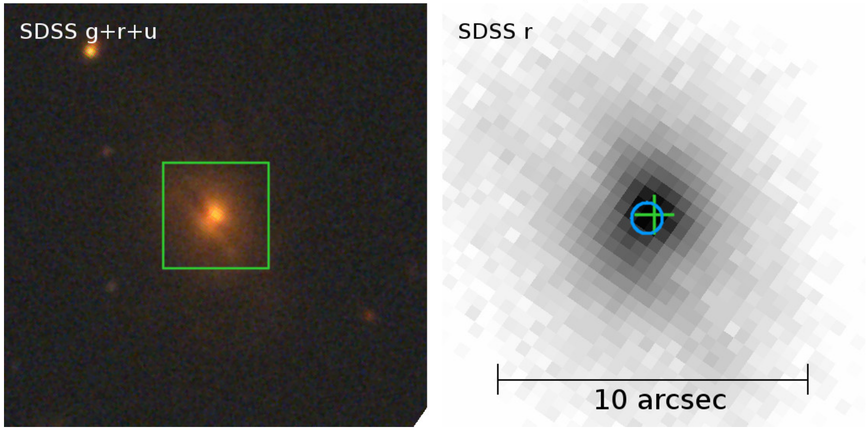


SDSS J093551.58+612111.7 **(UGC 5101)**: A well-known interacting Seyfert 1 galaxy (z = 0.0393) with an observed offset of 306 mas (245 pc).

Results – Galaxies with dust lanes

15 galaxies with CLASS/SDSS offsets of between **150** and **200 mas**
26 galaxies with offsets of between **200** and **600 mas**
3 further galaxies with an offsets of more than **600 mas**

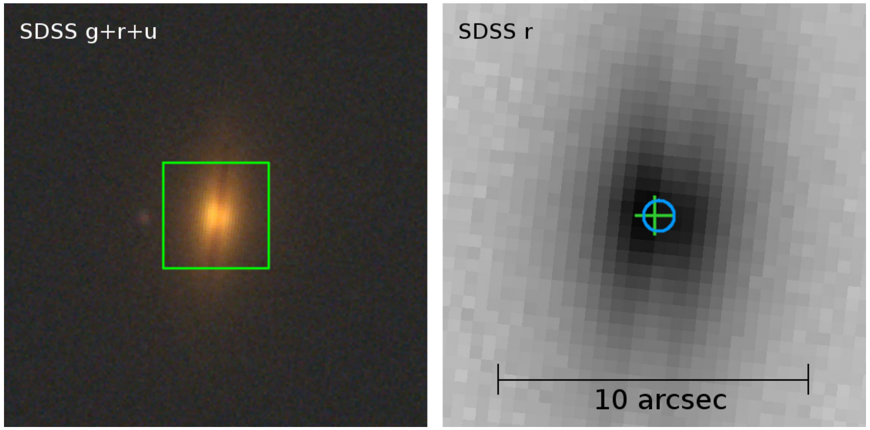
OSSY ID: 588013382729859273, RA 09h14m45.53s, Dec 41d37m14.28s



SDSS J091445.53+413714.2: A little-known galaxy ($z = 0.141$) with a faint 9.8 mJy CLASS detection offset by 357 mas (971 pc). There is a clear dust lane in the SDSS image.

Skipper & Browne, submitted to MNRAS

OSSY ID: 587734948056727714, RA 10h25m44.22s, Dec 10d22m30.48s

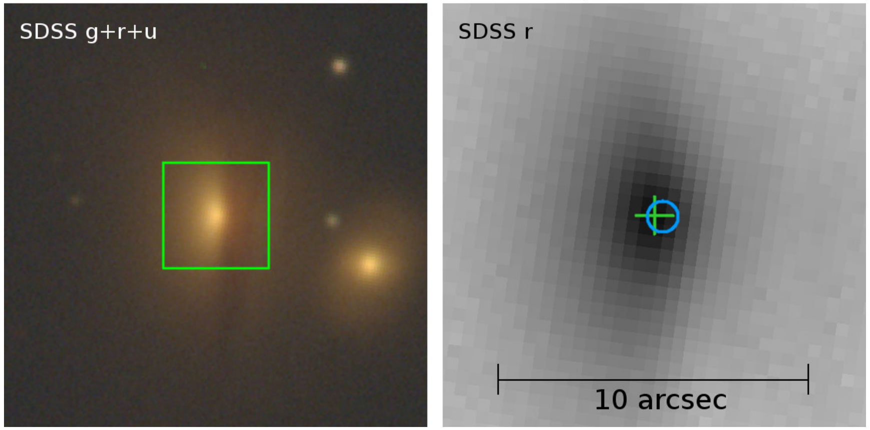


SDSS J102544.22+102230.4: A little-known S0 spiral galaxy ($z = 0.0457$) with a CLASS detection of 50.0 mjy offset by 220 mas (204 pc).

Results – Galaxies with dust lanes

15 galaxies with CLASS/SDSS offsets of between **150** and **200 mas**
26 galaxies with offsets of between **200** and **600 mas**
3 further galaxies with an offsets of more than **600 mas**

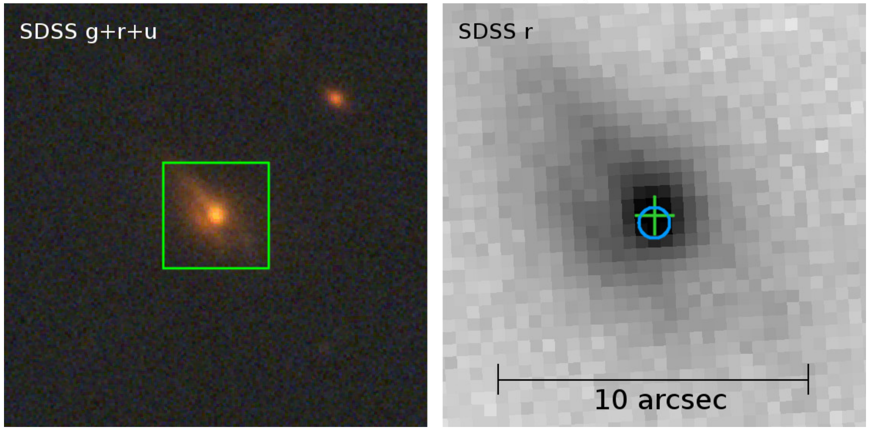
OSSY ID: 587741602562310202, RA 11h11m25.21s, Dec 26d57m48.97s



SDSS J111125.21+265748.9 **(NGC 3563B)**: A SB0 spiral galaxy ($z = 0.0336$) with a 20.3 mJy CLASS detection offset by 245 mas (168 pc). Part of the NGC 3563 pair of interacting galaxies, and hosts a prominent dust lane to the west of the nucleus.

Skipper & Browne, submitted to MNRAS

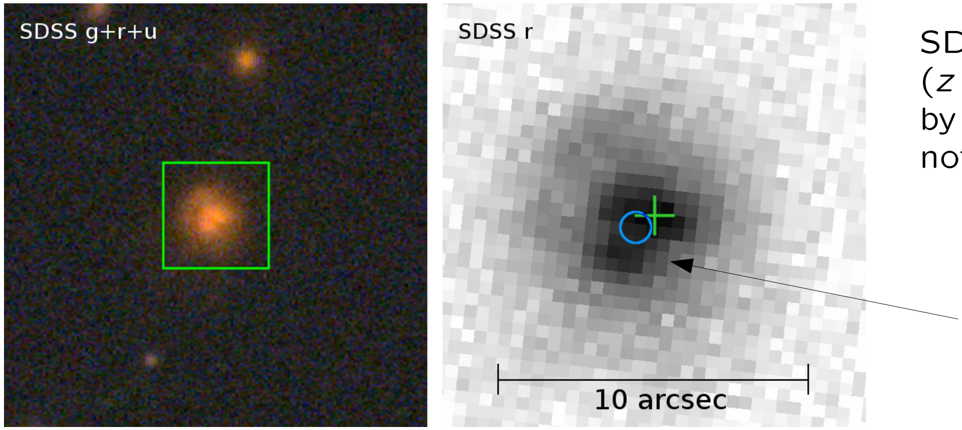
OSSY ID: 588023668102004902, RA 12h54m33.26s, Dec 18d56m02.17s



SDSS J125433.25+185602.1: A little-known spiral galaxy ($z = 0.115$) with a strong CLASS detection of 128.2 mjy, offset by 273 mas (617 pc). This source lies within Abell 1638, and hosts a clear dust lane.

15 galaxies with CLASS/SDSS offsets of between **150** and **200 mas**
26 galaxies with offsets of between **200** and **600 mas**
3 further galaxies with an offsets of more than **600 mas**

OSSY ID: 587731870170349772, RA 11h50m00.07s, Dec 55d28m21.32s

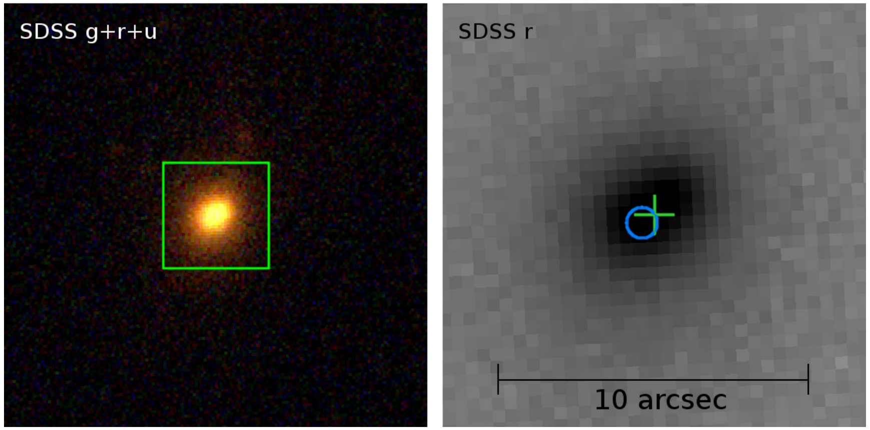


SDSS J115000.07+552821.3: A Seyfert galaxy (z = 0.139) with a 70 mJy CLASS detection, offset by 1.13 arcsec (3,030 pc). AGN offset previously noted by de Vries et al (2009).

CLASS detection of 70.0 mJy

Skipper & Browne, submitted to MNRAS

OSSY ID: 587741531719270424, RA 12h41m35.08s, Dec 28d50m36.50s

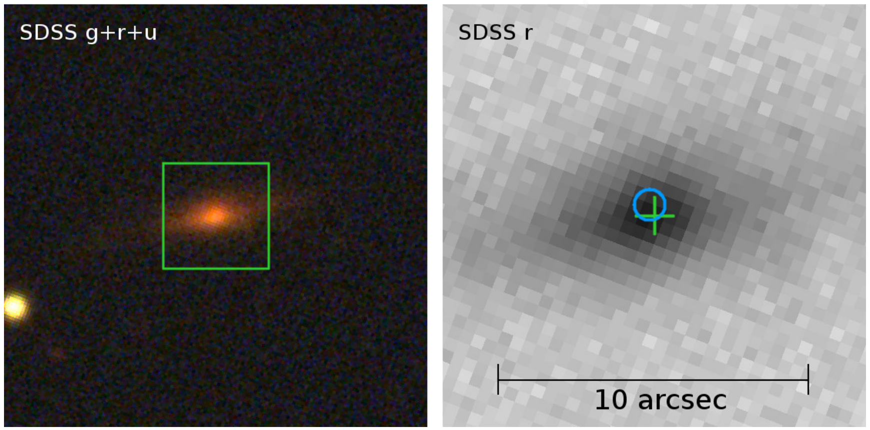


SDSS J124135.08+285036.5: A little-known galaxy (z = 0.0664) with a 31.4 mJy CLASS detection offset by 467 mas (623 pc). Also selected as an offset-AGN candidate by Comerford & Greene (2014) on the basis of a spectral-line offset.

Results – Strong offset-AGN candidates

15 galaxies with CLASS/SDSS offsets of between 150 and 200 mas
26 galaxies with offsets of between 200 and 600 mas
3 further galaxies with an offsets of more than 600 mas

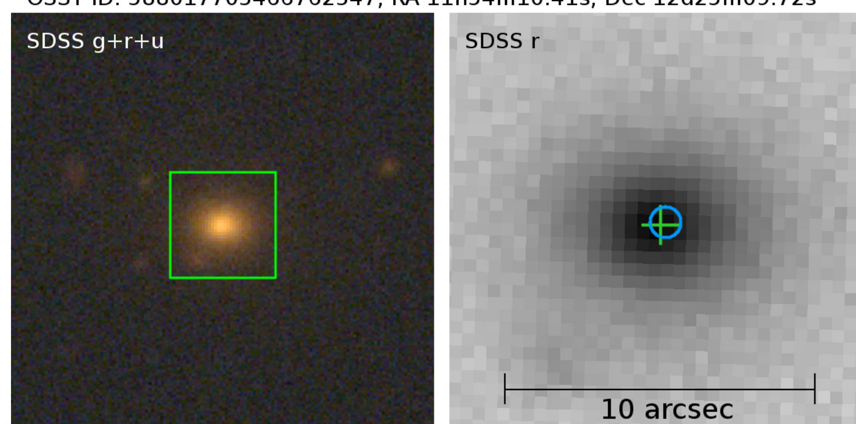
OSSY ID: 587741816772493607, RA 08h29m05.45s, Dec 14d04m06.74s



SDSS J082905.46+140406.7: A little-known galaxy ($z = 0.137$) with a CLASS detection of 22.3 mJy, offset by 239 mas (635 pc). OSSY line strenths indicate a LINER, and SDSS images hint at a late-type morphology.

Skipper & Browne, submitted to MNRAS

OSSY ID: 588017703466762347, RA 11h54m10.41s, Dec 12d25m09.72s

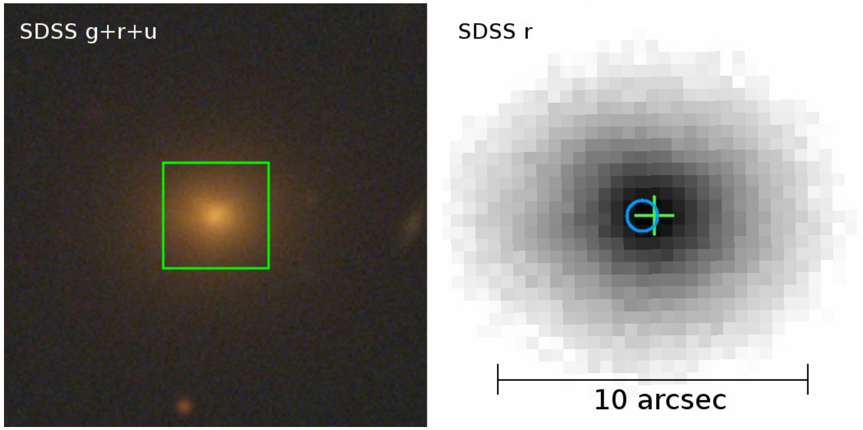


SDSS J115410.41+122509.7: A little-known galaxy ($z = 0.0812$) with a strong 187.5 mJy CLASS detection offset by 221 mas (358 pc). The spectrum shows very strong narrow lines, especially [O_{II}].

Results – Strong offset-AGN candidates

15 galaxies with CLASS/SDSS offsets of between **150** and **200 mas**
26 galaxies with offsets of between **200** and **600 mas**
3 further galaxies with an offsets of more than **600 mas**

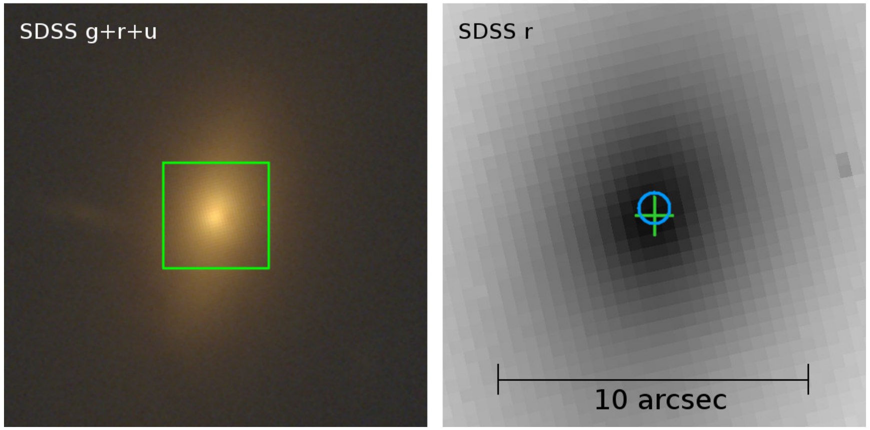
OSSY ID: 587739608627937400, RA 12h25m13.09s, Dec 32d14m01.58s



SDSS J122513.09+321401.5: A little-known nearby galaxy ($z = 0.0590$) with a CLASS detection of 80.5 mJy, offset by 408 mas (485 pc). Host is a large early-type galaxy which we classify as a LINER.

Skipper & Browne, submitted to MNRAS

OSSY ID: 587739304762081386, RA 13h50m36.01s, Dec 33d42m17.37s



SDSS J135036.01+334217.3 (NGC 5318 NED01): A nearby LINER galaxy ($z = 0.0144$) with a strong 95.8 mJy CLASS detection offset by 208 mas (62 pc).

The different results from X-ray and radio-selected samples

The radio-selected sample has far fewer sources offset from the galaxy centre by more than 600 mas than the X-ray-selected sample. Possible reasons:

- CONTAMINATION: X-ray selected samples may be contaminated by X-ray binaries and ULXs, which may be brighter in X-ray than the AGN.
- SELECTION EFFECTS: X-ray surveys typically impose minimum luminosities, and the fraction of offset AGN is known to increase with bolometric luminosity (Comerford & Green, 2014).
- ASTROMETRY: Radio positions are much more accurate than X-ray positions.
- EVOLUTION: It is possible that the radio emission switches on at a much later stage of the merger process than the X-ray emission. i.e. after the SMBH binaries have coalesced. Delayed triggering of radio AGN has been invoked by (for example) Shabala et al (2017).

What next ?

- First paper submitted to MNRAS ✔
- Follow-up observations:

  Detailed radio and optical observations of several of the stronger offset-AGN candidates, such as SDSS J124135.08+285036.5 and SDSS J082905.46+140406.7.

  Focus on galaxies without NGC, Mrk, etc catalog references, and others without references in the literature.
- Expand survey beyond OSSY catalog, and repeat search using FIRST catalog instead of CLASS.
- Identify any offset-AGN candidates with archival HST coverage in order to better constrain the optical centroid.

Summary

We place an upper limit on the fraction of radio AGN that are offset from the optical centroid of their host galaxies of 17 %.

We expect that many of these candidates are the result of poorly-constrained optical centroids due to disturbed or irregular host morphologies.

We find only three from from our sample of 345 galaxies (0.87 %) have radio offsets of more than 600 mas, compared to 18 out of 48 (37.5 %) reported by Barrows et al (2016).

We have identified a number of interesting new offset-AGN candidates which will be followed up with further radio observations.